Mechanistic Study of the Transimination of Bis(*N*-alkylsalicylaldiminato)nickel(II) with Ammonium Ion in Acetonitrile

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Electronic spectrophotometry has been employed to study the mechanism of transimination in bis(*N*-alkylsalicylaldiminato)nickel(II) complexes (alkyl = Me, Et, Pr^i, Pr^n or Bu^n) by ammonium ion in acetonitrile. The reaction is clearly biphasic: fast addition of ammonium and slow elimination of alkylammonium ions. The addition reaction involving the two azomethine bonds of the complex occurs by two consecutive processes and a two-term rate law was found for R = Bu^n. In the successive elimination reaction only one rate constant was observed which depends on the pK_a and steric strain of the leaving alkylammonium ions.

Kinetic studies of the reaction of imines with amines (transimination or *trans*-Schiffization) have been carried out more or less thoroughly by a number of authors. This reaction is acid-catalysed and occurs by amine attack on the protonated or cationic imine, similarly to other addition reactions to this group.[1] The rate enhancements result from the fact that, although the >C=N–R group is not very reactive, the nitrogen basicity allows the formation of a highly reactive >C=NHR$^+$ group. The same type of catalysis is observed in transimination reactions involving pyridoxal (3-hydroxy-5-hydroxymethyl-2-methylpyridine-4-carbaldehyde) and pyridoxal phosphate[2] coenzymes. The pyridoxal phosphate binds to the amino group of a lysine enzyme residue forming a Schiff base[3] which reacts with an amine more readily than the starting carbonyl compound. Non-enzymatic pyridoxal-catalysed transimination reactions take place slowly in aqueous solutions. The addition of appropriate metal ions enhances the reaction rates, which however continue to be slow, and a catalytic effect may operate *via* formation of metal–Schiff base chelates acting as intermediates.[4] The role of the metal ion is unclear, even if in non-enzymatic reactions it appears to fulfil some of the roles played by the protein in enzymatic reactions.

For these reasons a programme in this laboratory was devoted to investigating the reactivity of Schiff base >C=N–R groups directly co-ordinated to metal ions in an aprotic solvent. We have recently found[5] that iminic groups of cobalt(II)–, nickel(II)– and copper(II)–Schiff base chelates give rise to a fast exchange reaction with ammonium or ammonium-like cations, including the amino acids. This paper reports on the mechanism of the transimination reaction between ammonium ion and bis(*N*-alkylsalicylaldiminato)nickel(II) complexes in acetonitrile.

Experimental

The bis(*N*-alkylsalicylaldiminato)nickel(II) complexes, [Ni(R-sala)$_2$] (sala = salicylaldiminate: R = H,[6a] Me,[6b] Et,[6b] Bu^n,[6b] Pr^n,[6b] or Pr^i [6b]), were prepared according to the methods described in the literature and recrystallized from appropriate solvents. Melting points and elemental analyses confirmed the purity of each complex.

The ^{15}N-labelled [Ni(H-sala)$_2$] was prepared from [Ni(Bu-sala)$_2$] (1 g, 2.4 mmol) and [$^{15}NH_4$]$_2$[SO$_4$] (30.9% ^{15}N; 0.6 g, 4.5 mmol) in acetonitrile (50 cm^3). The solution was stirred for 30 min at room temperature and a red solid (yield 90%) precipitated. The solid was recrystallized and dried under vacuum. The mass spectrum of the product was indicative of the formation of [Ni(sala)$_2$] containing 0, 1 or 2 atoms of ^{15}N in the proportions of 49, 41 and 10% respectively, consistent with the percentages expected for a statistical exchange between the starting complex and the enriched NH_4^+ used.

Ammonium and ethylammonium tetraphenylborate were obtained by precipitation from aqueous solutions of the corresponding chlorides with sodium tetraphenylborate, while tetra-n-butylammonium tetraphenylborate was a C.Erba product. These salts were recrystallized three times from toluene–acetone. All compounds were dried at 50 °C under vacuum prior to use. Acetonitrile was carefully purified and dried by standard methods;[7] residual water (< 1 ppm) was estimated using the modified Karl–Fischer method (Metrohm).

The IR spectra were recorded on a Perkin-Elmer model 983 spectrophotometer by using 0.5 mm KBr cells and tetrahydrofuran–acetonitrile (3:2 v/v) as solvent, mass spectra on a VG model 70-70E instrument.

Kinetic Measurements.—The reactions were studied at 25 ± 0.1 °C by monitoring the largest change in absorbance between the starting and the final spectra. The substrate concentration was (1–3) × 10^{-4} mol dm^{-3} and the ammonium tetraphenylborate was used in large excess (20–100 fold). The ionic strength of the solutions was held constant by adding NBu_4BPh_4, which is inert towards the nickel complexes. In acetonitrile all the electrolytes were assumed to be completely dissociated[8] and were spectrophotometrically inactive in the explored range of the wavelengths. The reactions with $t_{\frac{1}{2}}$ > 10 s were followed at the selected wavelength by using a Perkin-Elmer Lambda-15 spectrophotometer connected to a personal computer. In all cases the spectra at 'infinite time' were identical to those recorded for the expected products, under the same experimental conditions. More than 150 absorbance values were collected in a single run. The reacting solutions were prepared in a 1 cm optical path cell (specifically planned to keep the solutions under a nitrogen atmosphere). The faster reactions ($t_{\frac{1}{2}}$ < 10 s) were followed by use of a stopped-flow spectrophotometer constructed by us to a design kindly provided by the Max-Planck-Institut für Biophysikalische Chemie. This apparatus offers the advantage of working under an inert atmosphere at controlled temperature. The acquisition of the signal from the photomultiplier (up to a maximum of 15 000 data) takes place *via* a 8035 microprocessor with a 12-bit analogue-digital converter. The time-scale can vary from 0.1 to 70 ms and the dead-time is 6–8 ms. Instrument control

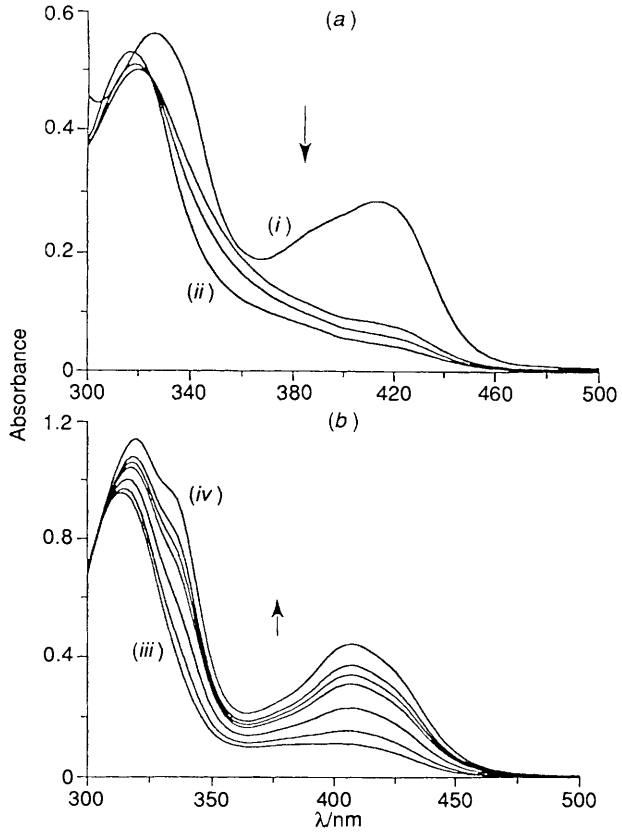


Fig. 1 Spectral changes in the reaction of [Ni(Bu-sala)$_2$] [0.80 × 10^{-4} for (*a*), 1.3 × 10^{-4} mol dm^{-3} for (*b*)] and NH_4BPh_4 [2.0 × 10^{-4} for (*a*), 1.6 × 10^{-2} mol dm^{-3} for (*b*)] in acetonitrile at 25 °C. (*a*) (*i*) Spectrum of [Ni(Bu-sala)$_2$]; (*ii*) last spectrum recorded 120 s after mixing of the reagents. (*b*) The first spectrum (*iii*) was recorded about 120 s after mixing of reagents; the last spectrum (*iv*) was recorded after 4 h

Table 1 Coefficients $A_{\infty 1}$, α_1 and α_2 of equation (3) describing the first phase of the reaction between [Ni(Bu-sala)$_2$] and NH_4BPh_4 in acetonitrile at 25 °C[a]

$10^2[NH_4^+]$/ mol dm^{-3}	10^4[Ni(Bu-sala)$_2$]/ mol dm^{-3}	α_1/s^{-1}	α_2/s^{-1}	$A_{\infty 1}$
1.50	2.1	10.56	1.71	0.112
1.35	2.1	9.77	1.50	0.110
1.05	2.1	7.24	1.10	0.110
0.81	1.9	5.35	0.89	0.095
0.75	2.1	5.22	0.83	0.112
0.72	1.9	4.53	0.72	0.108
0.60	2.1	4.42	0.69	0.120
0.57	1.9	3.78	0.61	0.116
0.45	1.9	3.35	0.53	0.131
0.36	1.9	2.67	0.43	0.142
0.19	2.1	—	—	0.217

[a] I = 0.03 mol dm^{-3} (NBu_4BPh_4), λ = 410 nm. Relative standard deviations are ≤7 × 10^{-3}.

and real-time display of the results are provided by a personal computer. Only such runs which could be reproduced at least twice were evaluated by a computer program. A total of 1500 data points were collected for each run. The experimental data were fitted by an appropriate exponential function using a non-linear least-squares iterative method (CFT4 and VARPAR programs).[9,10]

Results and Discussion

As reported in a previous paper,[5] the addition of NH_4BPh_4 to a

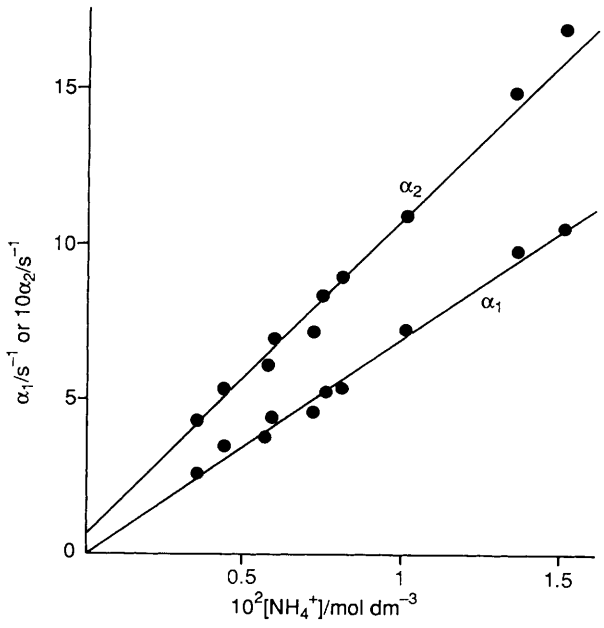


Fig. 2 Plots of α_1 and α_2 *vs.* $[NH_4^+]$, where α_1 and α_2 are the exponential factors in equation (3), for the reaction of [Ni(Bu-sala)$_2$] with NH_4BPh_4 in acetonitrile at 25 °C and I = 0.03 mol dm^{-3}

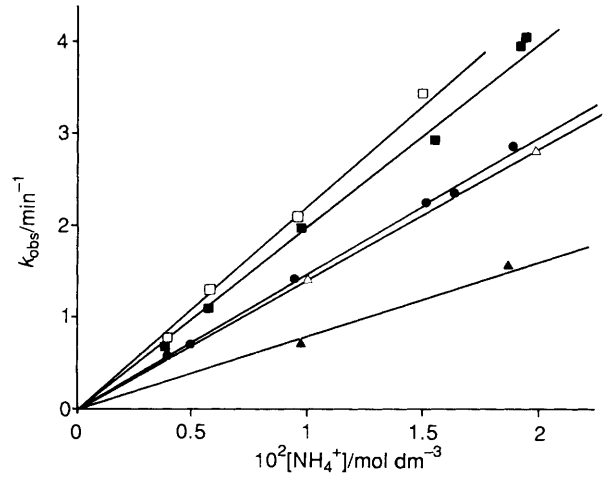


Fig. 3 Plots of the pseudo-first-order rate constants against ammonium concentration for the second slow phase of reaction (1) in acetonitrile at 24.6 °C and I = 0.03 mol dm^{-3}. R = Me (□), Et (■), Pr^n (△), Bu^n (●), or Pr^i (▲)

[Ni(R-sala)$_2$] solution results in a transimination reaction in which the alkyl group R is replaced by hydrogen [equation (1)].

$$[Ni(R\text{-}sala)_2] + 2NH_4^+ \rightleftharpoons [Ni(H\text{-}sala)_2] + 2NH_3R^+ \quad (1)$$

Reaction (1) represents a particular case of the general equilibrium (2).

$$[Ni(R\text{-}sala)_2] + 2NH_3R^+ \rightleftharpoons [Ni(R\text{-}sala)_2] + 2NH_3R^+ \quad (2)$$

As clearly shown by mass spectrometry, the use of $^{15}NH_4^+$ leads to incorporation of ^{15}N into the reaction product, confirming the exchange of the iminic with the ammonic nitrogen. The electronic spectra collected during reaction (1) for the n-butyl derivative (Fig. 1) give a hint of the complexity of this reaction and reveal some phases of the process. After mixing with a stoichiometric quantity of NH_4^+, the complex [Ni(Bu-sala)$_2$] gives rise to a rapid spectral change which is completed in

Table 2 Rate constants for the second phase of the reaction between [Ni(R-sala)$_2$] and NH_4BPh_4 in acetonitrile[a]

R (T/°C)	$10^2[NH_4^+]$/ mol dm^{-3}	10^2k_{obs}/ min^{-1}	$k_{obs}[NH_4^+]$/ dm^3 mol^{-1} min^{-1}
Me	1.50	3.42	
(24.6)	0.96	2.07	2.2 ± 0.25
	0.58	1.30	
	0.39	0.78	
Et	1.94	4.03	
(24.6)	1.93	3.94	
	1.55	2.90	2.0 ± 0.11
	0.97	1.98	
	0.58	1.09	
	0.39	0.68	
Pr^n	1.99	2.81	1.4
(24.6)	1.00	1.43	
Pr^i	1.87	1.58	0.8
(24.6)	0.97	0.73	
Bu^n[b]	1.89	1.50	
(14.9)	1.44	1.20	0.82 ± 0.03
	0.75	0.63	
	0.37	0.30	
Bu^n[b]	1.89	2.83	
(24.6)	1.63	2.31	
	1.51	2.21	1.48 ± 0.02
	0.94	1.42	
	0.49	0.72	
	0.38	0.56	
Bu^n[b]	1.89	7.46	
(40.0)	1.53	5.64	
	0.75	3.06	3.8 ± 0.11
	0.38	1.56	
	0.37	1.59	
	0.19	0.84	
Bu^n[c] (25)	3.5	6.42	1.6

[a] [Ni(R-sala)$_2$] = (1–3) × 10^{-4} mol dm^{-3}, I = 0.03 mol dm^{-3} (NBu_4BPh_4); λ = 410 nm. Standard errors were calculated by the VARPAR program. [b] The activation parameters are $\Delta H^{\ddagger}$ = 46 kJ mol^{-1} and $\Delta S^{\ddagger}$ = −97 J K^{-1} mol^{-1}. [c] Data obtained by IR measurements in acetonitrile–tetrahydrofuran (3:2 v/v). The choice of the solvent was determined by problems of solubility and transparency to IR.

about 100 s [Fig. 1(*a*)], followed by a slower change [Fig. 1(*b*)]. Correspondingly, the following phenomena can be highlighted.

(*a*) The absorption peak at 410 nm, typical of the complexes studied, decreases rapidly in the initial phase [Fig. 1(*a*)], and then starts to grow more slowly [Fig. 1(*b*)]. (*b*) In this second phase the shoulder typical of the [Ni(H-sala)$_2$] spectrum appears at 335 nm. (*c*) The absorbance spectra in Fig. 1(*a*) have an isosbestic point at 323 nm. Neither the spectrum of the starting complex nor those recorded during the second phase pass through this point. Similar trends were also observed for the other nickel complexes studied. By IR analysis, it was shown that after addition of the ammonium salt the initial intensity of the band at 1613 cm^{-1} [ν(C=N)] rapidly decreased followed by a slow increase in accord with the slow reaction step monitored by UV/VIS spectroscopy. Therefore, the changes in absorbance recorded at 410 nm can be related to a rapid iminic double-bond breaking, followed by its slow reformation. In this respect, it must be pointed out that the absorption band at 410 nm is generally assigned[11] to one of the two $\pi \longrightarrow \pi^*$ transitions of the quinonic form of the Schiff base and it is enhanced by metal chelation.[12] Therefore, the absorbance depression observed at 410 nm can be attributed to the formation of one or more intermediate compounds unable to resonate in the quinonic form. However, when [Ni(H-sala)$_2$] was treated with an excess of $[NH_3R]BPh_4$ (R = Me, Et, or Bu^n), only a slow, monophasic reaction took place, in which the decrease in absorbance at 410 nm was not followed by an increase. In these cases, unlike that which occurs under preparative conditions[5] where other factors (*e.g.* the slow solubility of the final complex) can shift the equilibria, the reaction does not proceed beyond the formation of the intermediates.

The absorbance *vs.* time data for the faster step, collected by the stopped-flow apparatus for the [Ni(Bu-sala)$_2$] system, can be best fitted to a two-exponential function according to equation (3), typical of a two-sequence first-order process.[13] The

$$A_t = A_{\infty 1} + a_1 e^{-\alpha_1 t} + a_2 e^{-\alpha_2 t} \quad (3)$$

dependence of the $A_{\infty 1}$ value on NH_4^+ concentration (Table 1) is suggestive of an equilibrium in this reaction phase. The successive slow absorbance increase can be represented by the usual first-order equation (4); A_t, A_{o2}, $A_{\infty 1}$ and $A_{\infty 2}$ in equations

$$A_t = A_{\infty 2} + (A_{o2} - A_{\infty 2})e^{-k_{obs}t} \quad (4)$$

(3) and (4) represent the absorbance values at different times, at the start of the second phase and at the 'infinite time' in the first and second phases of the reaction, respectively. Tables 1 and 2 and Figs. 2 and 3 summarize the kinetic results obtained by equations (3) and (4) for the different systems studied. On the basis of the kinetic data and of the previous observations, a detailed description of the reaction mechanism is given in Scheme 1.

The formation of the intermediate **IIa**, which ends the first phase of the reaction, occurs through two consecutive equilibria (k_1/k_{-1}, k_2/k_{-2}) as required by equation (3), which are both followed by a fast intramolecular rearrangement equilibrium (K_i, K_i). The rate-determining steps are represented by the ammonium ion attacks on the polarized azomethine bonds in almost concerted mechanisms. These may be facilitated by the quinonic resonance form of the ligands,[2a,14] in which electron pairs are available on the iminic nitrogens. The pathways from **I** to **Ia** and from **II** to **IIa** take place through a sequence of fast steps involving both intramolecular proton exchanges between the geminal nitrogen atoms and bond breaking and making between nickel and geminal nitrogens.

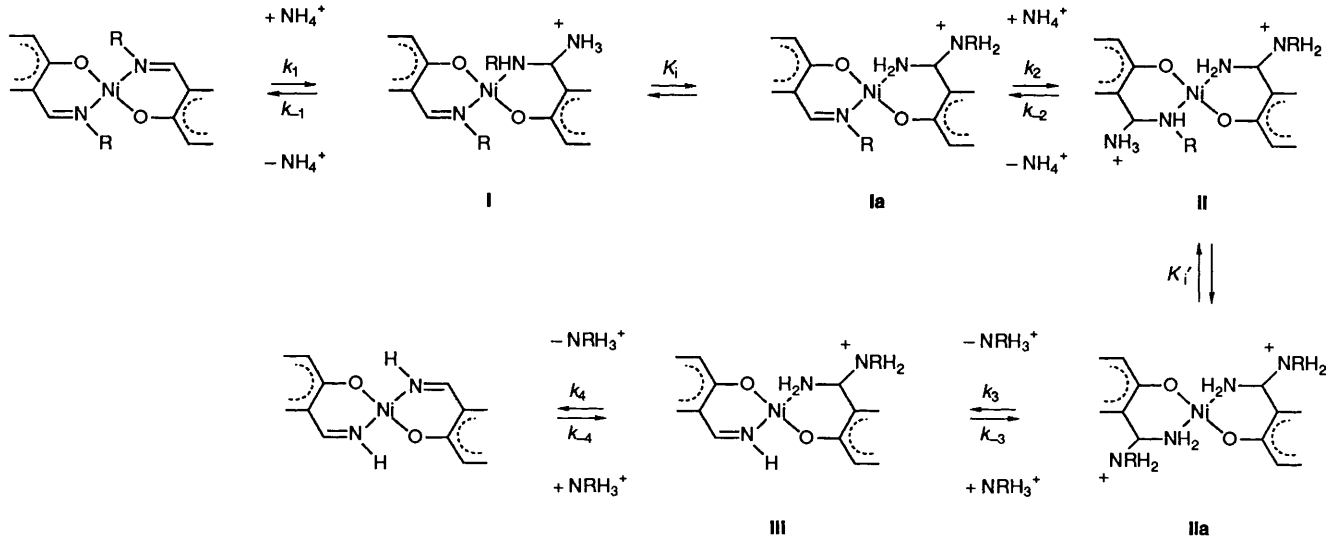
The absorbance spectra shown in Fig. 1(*a*) [see observations in point (*c*)] imply that at the end of the first phase of the reaction the starting complex has disappeared completely (*i.e.* the equilibria leading to the intermediate **Ia** are strongly shifted to the right). The observed dependence of $A_{\infty 1}$ on $[NH_4^+]$ (Table 1) suggests the presence of other species in equilibrium with the intermediate **IIa**. Therefore, by assuming k_{-1} as negligible, the analytical expressions of α_1 and α_2[13] are reduced to (5) and (6). The linear plots of α_1 and α_2 (Table 1) *versus*

$$\alpha_1 = k_1[NH_4^+] \quad (5)$$

$$\alpha_2 = \frac{k_{-2}}{1 + K_i} + \frac{k_2 K_i}{1 + K_i} \cdot [NH_4^+] \quad (6)$$

$[NH_4^+]$ shown in Fig. 2 are in accordance with equations (5) and (6) and give the numerical expressions $\alpha_1 = (7.0 \pm 0.13) \times 10^2[NH_4^+]$ and $\alpha_2 = (4 \pm 2) \times 10^{-2} + (1.04 \pm 0.05) \times 10^2[NH_4^+]$.

In order to obtain the final product [Ni(H-sala)$_2$], two NH_3R^+ groups must be expelled from the intermediate **IIa** in two successive steps which mechanistically correspond to the loss of two NH_4^+ ions from **IIa** to give the starting complex [Ni(R-sala)$_2$]. Only one kinetically detectable step for this slow reaction phase was found and it is first order in the concentrations of both the complex and ammonium (Fig. 3). The initial absorbance values of this reaction phase (A_{o2}) coincide with those observed at the end of the first phase ($A_{\infty 1}$) which shows that the formation of **III** is rate-determining. This step is followed by a fast equilibrium reaction shifted strongly towards the product [Ni(H-sala)$_2$], as confirmed by the



Scheme 1

UV/VIS spectra recorded at 'infinite time' which correspond to that of the product. The analytical expression of k_{obs} for this reaction phase is of the type (7). The observed linear dependence

$$k_{obs} = \frac{k_3 K_2 K_i K_i' [NH_4^+]}{1 + K_2 K_i K_i' [NH_4^+]} \quad (7)$$

of k_{obs} (Table 2) on $[NH_4^+]$ (Fig. 3) is consistent with equation (7), assuming $K_2 K_i K_i' [NH_4^+] \ll 1$ in the range of $[NH_4^+]$ explored.

Taking into account the different terms in the expressions (5)–(7) for k_{obs}, α_1 and α_2, it is difficult to apportion the global effects encountered both on the single values of the rate constants and on the activation parameters $\Delta H^‡$ and $\Delta S^‡$ (Table 2). For example, the more the alkyl group bound to nitrogen increases the basicity of the iminic nitrogen, the more it will facilitate the addition equilibria (K_1 and K_2), but an increase in basicity correspondingly lowers the value of k_3. At the same time, the steric hindrance of the alkyl group delays the addition reaction, favours the expulsion reaction and exerts practically no influence on the intramolecular proton exchanges. On this basis can also be interpreted the inability of the more basic and sterically hindered NH_3R^+ cations to substitute the NH_4^+ ions.

In conclusion, the driving reaction force may be attributed to the relative acidities and steric factors of the attacking and leaving ammonion ions, as well as to the polarizing effect of nickel. The present investigation evidences the different reactivity of two identical ligands bound to the same metal. The mechanism proposed for the transimination reaction takes these different reactivities into account in both the phase of addition to the double iminic bond and in the successive elimination pathway. Furthermore, indirect evidence is provided for the build-up of a geminal amine intermediate whose existence has often been questioned in the past[2a,14] and for which a stabilizing effect by metal ion has been suggested.[15]

Acknowledgements

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